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Simulant Melt Experiments on Boiling Heat Transfer at the Upper Surface of Molten Metal

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1. Introduction

External Reactor Vessel Cooling (ERVC) via cavity flooding is adopted as one of the major severe accident management strategies in the APR1400 (Advanced Power Reactor 1400 MWe) and the current operating nuclear power plant, OPR1000 (Optimized Power Reactor 1400 MWe) [1]. The ERVC appears to be a viable means for an in-vessel retention (IVR) of corium for small and medium sized power reactors such as the Westinghouse AP-600, but it is not verified if currently proposed ERVC without additional enhancements could provide sufficient heat removal for high power reactors up to 1500 MWe. Especially, the thermal focusing effect of metallic layer is one of the most serious factors which threaten the integrity of the reactor pressure vessel (RPV). To mitigate the focusing effect of metallic layer, late in-vessel coolant injection is accompanied by the ERVC as the severe accident management strategies in the APR1400.

According to the experimental results of the relevant researches, there are discordant views in the heat removal capacity at the upper surface of the metallic layer when in-vessel coolant injection is active [2, 3, 4, 5]. In terms of thermal margin related with the focusing effect, in-vessel injection after ERVC provides an increased margin from thermal and mechanical failures. However, in case of large aspect ratio (i.e. thin-thick layer of less than 30cm), thermal margin is not sufficient with the film boiling heat removal at the upper surface of the metallic layer [6].

In this study, sustained heating experiments, named ELIAS (**E**xperiments on **L**ate-phase coolant **I**njection to **AS**sess the mitigation of focusing effect of metallic layer), were performed to quantify the heat removal rate at the upper surface of metallic layer for the precise evaluations on the effect of a late in-vessel coolant injection.

2. Descriptions of ELIAS Experiments

In the ELIAS experiments, pure Zinc is used as the simulant of metallic layer and bottom heating via catridge heater plate is adopted to simulate the heat transfer from the oxidic pool in the severe accident. The test section is rectangular shape having 0.2m in width and 0.3m in length. The heat flux from the bottom catridge heater is 675kW/m^2. The test section was made of carbon steel having 2mm-thick stainless steel liner for retarding rust. Table 1 shows the comparison between the ELIAS experiments and the reactor conditions for the metallic layer configurations and the heat flux from the bottom. Although there are limitations resulting from use of simulant melt, wide range of boiling regime up to film boiling can be simulated in the ELIAS experiments, which enables us to practically investigate the heat removal capacity at the upper surface of melt pool.

Table 1. Comparison of the ELIAS experiments and reactor conditions

	Melting Temp.(^{o}C)	Pr	Aspect Ratio(R/H)	Heat Flux (kW/m^2)
ELIAS	419.5	0.035	2.5 ~ 3.75	675
Reactor	~ 1500	0.128	~ 5.25	980 ~ 1580

Figure 1 shows the schematic diagram of the ELIAS experiments. Once the Zinc pool was heated to the desired temperature, water was injected onto the melt surface. To prevent an energetic melt coolant interaction, water was drained onto the melt pool via the brim of the test section. The outer surface of the test section was insulated to minimize the heat loss to the atmosphere.

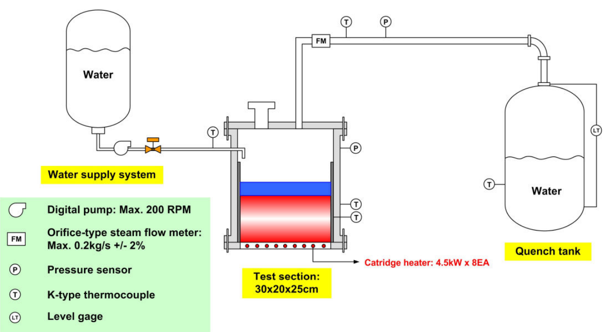

Figure 1. Schematic diagram of the ELIAS experiments

The heat removal rates at the upper surface of the melt pool were estimated using the temperature history of the melt pool. Total 36 K-type thermocouples were installed inside the melt pool to measure the temperature variations of the melt pool. In the ELIAS experiments, the major experimental parameters were an aspect ratio of melt pool and temperature of the test section bottom. The temperature of melt pool surface varies depending on the temperature of the test section bottom. In the tests, the superheat of melt pool surface varied from 343.23 ^{o}C to 486.5 ^{o}C for the melt pool height of 8cm and 12cm.

3. Experimental Results

Once the water was poured onto the melt surface, the temperatures of the melt pool decreased from the top. Figure 2 shows the temperature histories of the melt pool in the AR-2-10 test which was performed for 12cm melt pool height under the melt surface superheat of 486.5 ^{o}C. Overall trends of melt pool temperature variations were similar in all the tests. For the investigation of boiling heat transfer characteristics, the cumulative upward heat transfer was calculated from the measured temperatures in each layer of the melt pool using Eq. (1).

$$Q=\sum_{i}^{m} m_i\left[c_{pl}(T_{oi}-T_s)+h_{fusion}+c_{ps}(T_s-T_{boiloff})\right] \qquad (1)$$

Where, i = melt layer, m_i = mass of melt layer, c_p = specific heat of melt, h_{fusion} = latent heat of fusion, T_{oi}, T_s, $T_{boiloff}$ = initial temperature, solidification temperature, temperature at end of boiling of melt, respectively.

Heat fluxes from the melt pool to the water pool varied from 250 to 550kW/m^2 depending on the experimental conditions. Heat fluxes increase in proportional to the surface superheat of melt pool. In this study, for the evaluations on the boiling heat removal characteristics, boiling heat fluxes were calculated using the Berenson's film boiling correlation and compared with the ELIAS experimental results. Figure 3 shows the boiling heat fluxes from the melt pool to the water in the ELIAS experiments and calculation results using the Berenson's film boiling correlation. In Figure 3, AR-1 experiments and AR-2 experiments stand for the cases of 8cm and 12cm melt pool height, respectively. According to Figure 3, heat fluxes in the ELIAS experiments are larger than those of calculation using the Berenson's film boiling correlation by 5 to 10 times, which indicates that effective heat removal was accomplished via late-phase coolant injection in the ELIAS experiments.

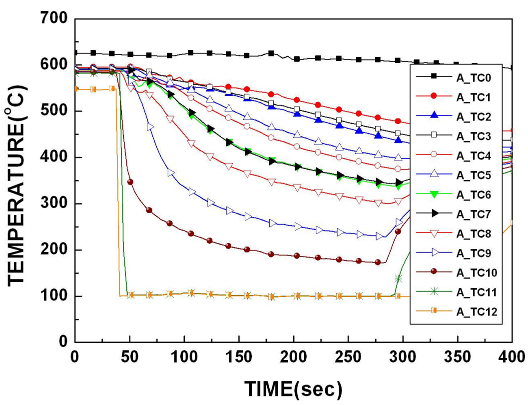

Figure 2. Temperature variations of melt pool in the AR-2-10 test: melt pool height = 12cm, surface superheat of melt pool = 486.5 ^{o}C

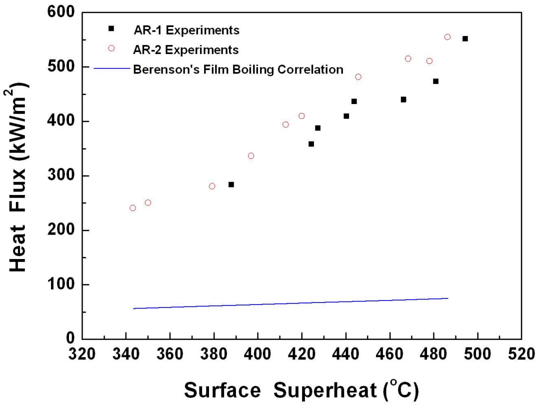

Figure 3. Heat fluxes from the melt pool to the water: comparison between ELIAS experimental results and calculation using the Berenson's film boiling correlation

4. Conclusion

In this study, sustained heating experiments, named ELIAS (**E**xperiments on **L**ate-phase coolant **I**njection to **AS**sess the mitigation of focusing effect of metallic layer), were performed to quantify the heat removal rate at the upper surface of metallic layer for the precise evaluations on the effect of a late in-vessel coolant injection. Heat fluxes from the melt pool to the water pool varied from 250 to 550kW/m^2 depending on the experimental conditions. Comparison of boiling heat fluxes between the ELIAS experiments and the calculation using the Berenson's film boiling correlation shows that effective heat removal was accomplished via late-phase coolant injection in the ELIAS experiments.

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